K^*-couplings for the antidecuplet excitation

Ya. Azimov[1], V. Kuznetsov[2,3], M. V. Polyakov[1,4], I. Strakovsky[5]

[1] Petersburg Nuclear Physics Institute,
Gatchina, 188300 Russia
[2]Kyungpook National University,
Daegu, 702-701, Republic of Korea
[3] Institute for Nuclear Research,
Moscow, 117312 Russia
[4] Institut für Theor. Physik -II, Ruhr-Universität,
D-44780 Bochum, Germany
[5] Center for Nuclear Studies, Physics Department,
The George Washington University,
Washington, DC 23606 USA

Abstract

We estimate the coupling of K^* vector meson to the $N \to \Theta^+$ transition employing the unitary symmetry, vector meson dominance, and results of the GRAAL Collaboration on the η photoproduction off the neutron. Our small numerical value of the coupling confirms that the CLAS Collaboration null results do not contradict to theoretical expectations for the Θ-production. We also estimate the K^*-coupling for the $N \to \Sigma^*$ excitation, with Σ^* being the Σ-like antidecuplet partner of the Θ^+-baryon.

1 Introduction

Experimental status of the exotic baryon Θ^+ looks to be rather uncertain. Various collaborations give either positive results on its observation, or null results casting doubts on existence of the Θ^+ and on correctness of its positive evidences (see recent experimental reviews [1, 2]). There are, however, no data of different groups with exactly overlapping conditions (initial and/or final states, kinematical regions, and so on). Therefore, when using today any null result of one group to reject a positive result of another group, we need to suggest some theoretical models/assumptions.

However, on this way, we also encounter numerous uncertainties. For instance, today's approaches to theoretical description of Θ-production (say, of its photoproduction off nucleon [3, 4, 5, 6, 7, 8, 9]) are mainly based on meson or reggeon exchanges K and K^*. The vertex for the $KN\Theta$-coupling may be considered as known, if one assumes the spin-parity and width of Θ^+ to be known (the corresponding form factor is still a problem, of course). However, properties of the K^* exchange are totally unknown. Meanwhile, they may be essential, as *e.g.*, in comparison of the Θ-photoproduction off the proton and/or the neutron.

In the present note, we are going to obtain at least rough estimates of the $K^*N\Theta$-coupling. Similar estimates will be provided for K^*-vertices of excitation $N \to \Sigma^*$. It will be done through relations of those vertices to the radiative vertex, extracted recently [10] from preliminary experimental data obtained by the GRAAL Collaboration [11] and confirmed, also preliminary, by the CB-ELSA-TAPS Collaboration [12].

2 Transition vertices

Let us consider transitions between two baryons $B_1 \to B_2$ through radiation of the photon or K^*. As the first step, we may assume the flavor symmetry $SU(3)_F$ to be exact. Then, the corresponding vertices for the vector meson octet are generated in QCD by the quark vector current J^a_μ. It is an octet in $SU(3)_F$, and the subscript a specifies its components. The electromagnetic current is also related (proportional, indeed) to one of those components. Since it conserves, and the $SU(3)_F$ is assumed to be exact, all other components should conserve as well. If both initial and final baryons have $J^P = 1/2^+$, then the transition vertex $V^a_\mu(B_2B_1)$ has, generally, the form

$$V^a_\mu(B_2B_1) = \langle B_2|J^a_\mu|B_1\rangle = \langle B_2| \left(f^a_1(B_1B_2)\gamma_\mu + f^a_2(B_1B_2)\frac{i\sigma_{\mu\nu}q^\nu}{M_1+M_2} + f^a_3(B_1B_2)\frac{q_\mu}{M_1+M_2}\right)|B_1\rangle\,, \quad (1)$$

where q is the momentum transfer, and form factors f^a_i are invariant functions of q^2.

In the present note, we are interested in transitions between baryons of different flavor multiplets and, hence, of different masses. Then, conservation of the current J^a_μ implies that f^a_1 is proportional to q^2 and, thus, disappears at $q^2 = 0$, in contrast to f^a_2. For the case of exact $SU(3)_F$, the last term of the vertex (1) does not provide any non-vanishing physically meaningful contribution (in total analogy with the similar term in the photon vertex).

Though the situation might change after accounting for violation of $SU(3)_F$, we advocate the tensor coupling (*i.e.*, the second term of Eq.(1)) to have the leading role at small q^2 for non-diagonal transitions. The relative contributions of other couplings should be suppressed. For the radiative decay $B_1 \to B_2\gamma$ (or $B_2 \to B_1\gamma$), with the real photon having $q^2 = 0$, only the second term in the vertex is physically meaningful, and

$$f_2(\gamma\, B_1\, B_2)\,|_{q^2=0} = \mu(B_1 \to B_2)\,(M_1 + M_2)\,, \quad (2)$$

where $\mu(B_1 \to B_2)$ is the magnetic transition moment.

Evidently, f_1 for diagonal transitions may not vanish at $q^2 \to 0$, though the 'tensor dominance" may still be true as well. Really, experimental data suggest that the ratio f_2/f_1 is large (~ 6) for the vertex ρNN, but is small (< 0.2) for the vertices ωNN and ϕNN [13]. The dominance of the tensor coupling over the vector one in hadronic non-diagonal transitions (between different flavor multiplets) is supported by the analysis [14] of data for transitions between **10** and **8** multiplets. Regretfully, many phenomenological calculations of Θ-production (*e.g.,* [3, 4, 5, 6, 7]) have used only the vector coupling for vector-meson exchanges, assuming non-vanishing $f^a_1|_{q^2\to 0}$ and neglecting $f^a_2(q^2)$. To our best knowledge, the dominance of the tensor coupling has been used only in Refs. [8, 9].

Now we are going to estimate the tensor couplings for the transitions $\mathbf{8} \to \overline{\mathbf{10}}$.

3 $\mathrm{SU(3)_F}$ relations

The ground state baryons, p and n in particular, belong to the unitary octet, which we consider to be (practically) unmixed. For the nonet of ground state vector mesons, we assume the ideal octet-singlet mixing, such that $\phi \sim s\bar{s}$, while ω corresponds to light quarks only. Both approximations are good enough for our present goals.

An octet baryon could not be transformed into one of an antidecuplet by a unitary singlet meson. Transition through coupling with an unitary octet meson is possible. Since the product $\mathbf{8}\times\mathbf{8}$ contains $\overline{\mathbf{10}}$ only once, all the appearing coupling constants may be expressed through one of them. The corresponding relations may be found by means of the Clebsch-Gordan coefficients for the group $SU(3)$. However, results look simpler and more transparent, if one uses combination of two $SU(2)$-subgroups of $SU(3)_F$: the familiar isotopic spin (I-spin) group, with the spinor (u,d) and singlet s, and the U-spin group, with the spinor (d,s) and singlet u.

The proton belongs to the U-spin doublet (p,Σ^+), with $U=1/2$, while the proton-like member of the antidecuplet, p^*, enters the U-spin quartet $(\Theta^+,p^*,\Sigma^{*+},\Xi^+_{3/2})$, with $U=3/2$. The vector meson nonet contains two independent U-singlet combinations, which cannot change U-spin and, thus, cannot transform $p\to p^*$. We may take them as $\rho^0+\omega$ and $\rho^0-\phi/\sqrt{2}$. This immediately gives us two relations

$$f_2(\rho^0\,p\,p^*) = -f_2(\omega\,p\,p^*) = \frac{1}{\sqrt{2}}\,f_2(\phi\,p\,p^*)\,. \tag{3}$$

The meson K^{*0} has $U=1$. It is a member of the U-spin triplet, other members of which are the combination $(\omega-\rho^0)/2-\phi/\sqrt{2}$ and $(-\overline{K}^{*0})$. The standard $SU(2)$ Clebsch-Gordan coefficients for the coupling $(1+1/2)\to 3/2$, being applied to this triplet, provide a simple relation

$$f_2(K^{*0}\,p\;\Theta^+) = -\sqrt{6}\,f_2(\rho^0\,p\,p^*)\,. \tag{4}$$

It is easy now to use standard isotopic relations and obtain neutron couplings

$$f_2(K^{*+}\;n\;\Theta^+) = -f_2(K^{*0}\,p\;\Theta^+),\quad f_2(\rho^0\,n\,n^*) = -f_2(\rho^0\,p\,p^*),\quad f_2(\omega\,n\,n^*) = f_2(\omega\,p\,p^*)\,, \tag{5}$$

where n^* is the n-like member of the antidecuplet; relation for ϕ-couplings is similar to that for ω.

In the same manner, one can find K^*-couplings to transitions between the nucleon and Σ^*, the Σ-like members of the antidecuplet. According to usual isotopic relations

$$f_2(\overline{K}^{*0}\,p\;\Sigma^{*+}) = -f_2(K^{*-}\;n\;\Sigma^{*-}) = -\sqrt{2}\,f_2(K^{*-}\,p\;\Sigma^{*0}) = \sqrt{2}\,f_2(\overline{K}^{*0}\;n\;\Sigma^{*0})\,, \tag{6}$$

while U-spin relations give

$$f_2(K^{*0}\,p\;\Theta^{*+}) = -\sqrt{3}\,f_2(\overline{K}^{*0}\,p\;\Sigma^{*+})\,. \tag{7}$$

Evidently, all the couplings may be expressed through one of them. We can take it to be, say, $f_2(\rho^0\,n\,n^*)$. Then, *e.g.*,

$$f_2(\overline{K}^{*0}\,p\;\Sigma^{*+}) = -\sqrt{2}\,f_2(\rho^0\,n\,n^*)\,,\qquad f_2(K^{*-}\,p\;\Sigma^{*0}) = f_2(\rho^0\,n\,n^*)\,. \tag{8}$$

In its turn, the ρ-meson coupling may be estimated starting from the transition magnetic moment.

4 Vector meson dominance

A good approximation for non-hard electromagnetic interactions of hadrons is the hypothesis that "the entire hadronic electromagnetic current operator is *identical* with a linear combination of the known neutral vector–meson fields" [15]. This approach is now known as the vector–meson dominance (VMD) [16] (for its recent brief review see the talk [17]).

The simplest form of VMD takes into account only the lightest mesons ρ^0, ω, and ϕ. Then the transition magnetic moments may be expressed as

$$\mu(B_1 \to B_2) = \frac{1}{M_1 + M_2} \sum_{V=\rho^0,\,\omega,\,\phi} \frac{e}{g_V}\, f_2(V\, B_1\, B_2)\, |_{q^2=0}\,. \tag{9}$$

In what follows, we will use $f_2(V\, B_1\, B_2)$ only at $q^2 = 0$, without showing this explicitly every time.

The meson-photon couplings g_V can be easily related to the partial widths of decays $V \to e^+e^-$:

$$\frac{g_V^2}{4\pi} = \frac{\alpha^2}{3}\, \frac{m_V}{\Gamma(V \to e^+e^-)}\,. \tag{10}$$

In assumption of exact $SU(3)_F$, the photon corresponds to the octet component with $U = 0$. Then the couplings g_V satisfy the group relations

$$\frac{1}{g_{\rho^0}} : \frac{1}{g_\omega} : \frac{1}{g_\phi} = 1 : \frac{1}{3} : (-\frac{\sqrt{2}}{3})\,. \tag{11}$$

For illustration, let us consider how these relations, together with other $SU(3)_F$ relations (3) and VMD relation (9), provide cancellation[1] of various contributions to $\mu(p^* \to p)$:

$$(M_p + M_{p^*}) \cdot \mu(p^* \to p) = \frac{e}{g_{\rho^0}}\, f_2(\rho^0\, p\, p^*) \left(1 - \frac{1}{3} - \frac{2}{3}\right) = 0\,. \tag{12}$$

Relations (11), with an additional assumption $m_V^{(0)} = m_V^{(8)}$, predict also that

$$\Gamma(\rho^0 \to e^+e^-) : \Gamma(\omega \to e^+e^-) : \Gamma(\phi \to e^+e^-) = 9 : 1 : 2\,. \tag{13}$$

Experimentally [2], these ratios look as

$$(7.0 \text{ keV}) : (0.6 \text{ keV}) : (1.3 \text{ keV}) = 11.6 : 1 : 2.1\,.$$

Evidently, $SU(3)_F$-violations are here less than 30%. Taking into account the difference of masses for ρ^0, ω, and ϕ, one can see that accuracy of ratios (11) is also not worse than 30%. Having in mind large current uncertainties in properties of $N^*(1675)$, which we assume to be the N-like partner of the Θ^+, we will use the $SU(3)_F$ relations as being precise.

Then, similar to the proton transition moment (12), we obtain the neutron transition moment

$$(M_n + M_{n^*}) \cdot \mu(n^* \to n) = \frac{e}{g_{\rho^0}}\, f_2(\rho^0\, p\, p^*) \left(-1 - \frac{1}{3} - \frac{2}{3}\right) = -\frac{2e}{g_{\rho^0}}\, f_2(\rho^0\, p\, p^*) = \frac{2e}{g_{\rho^0}}\, f_2(\rho^0\, n\, n^*)\,. \tag{14}$$

[1] In the exact $SU(3)_F$, the $\mu(p^* \to p)$ should vanish, since the U-spins are 3/2 for p^*, 1/2 for p, and 0 for the photon. After violation of $SU(3)_F$ this transition moment becomes non-vanishing, but is still much smaller than the $\mu(n^* \to n)$ [18].

5 Numerical estimates

Now we are ready to discuss numerical values of various quantities. Experimental characteristics of ρ^0 [2] and Eq.(10) give $|g_V| \approx 5$. Earlier in [10], we have extracted $|\mu(n^* \to n)| = (0.13 - 0.37)\,\mu_N$, where $\mu_N = e/(2M_N)$ is the standard nuclear magneton. This means that

$$|f_2(\rho^0\, n\, n^*)| = |f_2(\rho^0\, p\, p^*)| \approx (0.13 - 0.37)\; g_{\rho^0}\, \frac{M_N + M_{N^*}}{4M_N} \approx (0.45 - 1.28)\,. \tag{15}$$

It is essentially smaller than $|f_2(\rho^0\, N\, N)|$, which equals $12 - 16$ [13].

With the value (15), Eqs. (4) and (5) give

$$|f_2(K^{*0}\, p\, \Theta^+)| = |f_2(K^{*+}\, n\, \Theta^+)| = \sqrt{6}\, |f_2(\rho^0\, n\, n^*)| = (1.10 - 3.14)\,. \tag{16}$$

Analogously, from Eqs. (6) and (8) we can find also K^*-couplings for the Σ^*-excitation:

$$|f_2(K^{*-}\; p\; \Sigma^{*0})| = (0.45 - 1.28)\,, \quad |f_2(\overline{K}^{*0}\; p\; \Sigma^{*+})| = (0.64 - 1.81)\,. \tag{17}$$

Incidentally, the value of $f_2(K^{*+}\, n\, \Theta^+) = 1.1$, supported now by Eq.(16), has been earlier used in Ref. [9] to estimate the production cross section of Θ^+ in photoreactions[2]. With the width of Θ^+ of 1 MeV and the above value of $f_2(K^*\, N\, \Theta)$, calculations [9] provide small cross sections $\sigma_{tot}(\gamma p \to \overline{K}^0 \Theta^+) < 0.22$ nb and $\sigma_{tot}(\gamma n \to K^- \Theta^+) < 1$ nb, which are below the limits put recently by the CLAS Collaboration [20, 21]. To make more detailed comparison with the results of the CLAS Collaboration, we use the model of Ref. [9] and the above range (16) of K^* coupling constants to calculate the corresponding range of the Θ^+ production cross section in the process $\gamma + p \to \overline{K}^0 + \Theta^+$, depending on the photon energy, see Fig. 1. These calculations are compared with the corresponding upper limit put by the CLAS Collaboration in Ref. [20]. We see that, apart from the higher photon energy region, our estimate of the cross section is always below the limits put by the CLAS Collaboration. This comparison shows that the CLAS analysis procedure of Ref. [20] might be not sensitive enough to reveal Θ^+.

Surely, the estimate (16) is very rough, nevertheless it clearly shows that the coupling of the K^* to $N\Theta^+$ system is very small. Moreover, we expect that corrections due to nonzero mass of the strange quark may further reduce our estimate.

Acknowledgments

We are grateful to D. Diakonov for many discussions. The work was partly supported by the Russian State Grant RSGSS-1124.2003.2, by the Russian-German Collaboration Treaty (RFBR, DFG), by the COSY-Project Jülich, by the Sofja Kowalewskaja Programme of Alexander von Humboldt Foundation, BMBF, DFG Transregio, by the U. S. Department of Energy Grant DE–FG02–99ER41110, by the Jefferson Laboratory, and by the Southeastern Universities Research Association under DOE Contract DE–AC05–84ER40150.

[2]In Ref. [9] the value of $f_2 \approx 1.1.$ has been obtained from Chiral Quark-Soliton Model of Ref. [19]

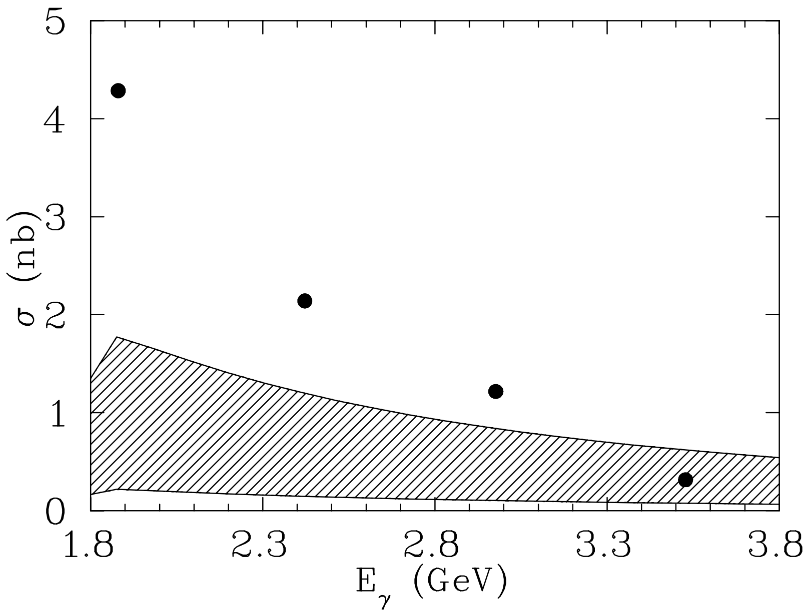

Figure 1: Shaded band corresponds to the range of Θ^+ production cross section in the process $\gamma + p \to \overline{K}^0 + \Theta^+$ as the function of the photon energy, expected according to model [9]. The lower and upper edges of the band correspond to the coupling constant values $|f_2(K^{*0}\, p\, \Theta^+)| = 1.10$ and 3.14, the range obtained in the present paper. The filled circles correspond to the experimental upper limits for the cross section put by the CLAS Collaboration [20].

References

[1] V. D. Burkert, Int. J. Mod. Phys. A **21**, 1764 (2006) [hep-ph/0510309].

[2] W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).

[3] Y. S. Oh, H. C. Kim, and S. H. Lee, Phys. Rev. D **69**, 014009 (2004) [hep-ph/0310019]; S. I. Nam, A. Hosaka, and H. C. Kim, hep-ph/0403009.

[4] F. E. Close and Q. Zhao, Phys. Lett. B **590**, 176 (2004) [hep-ph/0403159].

[5] Y. Oh, K. Nakayama, and T. S. Lee, Phys. Rept. **423**, 49 (2006) [hep-ph/0412363].

[6] A. I. Titov, B. Kämpfer, S. Date, and Y. Ohashi, Phys. Rev. C **72**, 035206 (2005) [Erratum-ibid. C **72**, 049901 (2005)] [nucl-th/0506072].

[7] W. Liu, C. M. Ko, and V. Kubarovsky, Phys. Rev. C **69**, 025202 (2004) [nucl-th/0310087].

[8] M. V. Polyakov, in *Proceedings of the Workshop on the Physics of Excited Nucleons (NSTAR2004), Grenoble, France, March, 2004*, eds. J.-P. Bocquet, V. Kuznetsov, and D. Rebreyend (World Scientific, 2004), p. 31 [hep-ph/0412274].

[9] H. Kwee, M. Guidal, M. V. Polyakov, and M. Vanderhaeghen, Phys. Rev. D **72**, 054012 (2005) [hep-ph/0507180].

[10] Y. Azimov, V. Kuznetsov, M. V. Polyakov, and I. Strakovsky, Eur. Phys. J. A **25**, 325 (2005) [hep-ph/0506236].

[11] V. Kuznetsov (GRAAL Collaboration), in *Proceedings of the Workshop on the Physics of Excited Nucleons (NSTAR2004), Grenoble, France, March, 2004*, eds. J.-P. Bocquet, V. Kuznetsov, and D. Rebreyend (World Scientific, 2004), p. 197 [hep-ex/0409032];
V. Kuznetsov, *"GRAAL search for non-strange members of the antidecuplet"*,
talk at international workshop on Exotic Baryons, Trento, February, 2005,
http://www.tp2.rub.de/vortraege/workshops/trento05/index.shtml?lang=de;
V. Kuznetsov (GRAAL Collaboration), hep-ex/0606065.

[12] I. Jaegle (for the CB-ELSA-TAPS Collaboration), in *Proceedings of the Workshop on the Physics of Excited Nucleons (NSTAR2005), Tallahassee, USA, October, 2005*, eds. S. Capstick, V. Crede, and P. Eugenio (World Scientific, 2006), p. 340.

[13] O. Dumbrajs *et al.*, Nucl. Phys. B **216**, 227 (1983).

[14] A. C. Irving and R. P. Worden, Phys. Rep. **34**, 117 (1977).

[15] N. M. Kroll, T. D. Lee, and B. Zumino, Phys. Rev. **157**, 1376 (1967).

[16] J. J. Sakurai, Phys. Rev. Lett. **22**, 981 (1969).

[17] D. Schildknecht, Acta Phys. Polon. B **37**, 595 (2006) [hep-ph/0511090].

[18] M. V. Polyakov and A. Rathke, Eur. Phys. J. A **18**, 691 (2003) [hep-ph/0303138].

[19] D. Diakonov, V. Petrov, and M. V. Polyakov, Z. Phys. A **359**, 305 (1997) [hep-ph/9703373].

[20] R. De Vita *et al.* (CLAS Collaboration), Phys. Rev. D **74**, 032001 (2006) [hep-ex/0606062].

[21] B. McKinnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. **96**, 212001 (2006) [hep-ex/0603028].